Carbon Storage in Coarse and Fine Fractions of Pacific Northwest Old-Growth Forest Soils

P. S. Homann,* S. M. Remillard, M. E. Harmon, and B. T. Bormann

ABSTRACT

Many assessments of soil C have been restricted to the <2-mm fraction, but C has recently been identified in >2-mm fractions of forest mineral soils. Our objective was to determine the importance of the >2-mm fraction to whole-soil C pools in Pacific Northwest old-growth coniferous forests. Seventy-nine pedons in 18 western Washington and Oregon forests were sampled to a depth of 100 cm. The <2-mm fraction was separated from the >2-mm fraction by air-drying, physically crushing soil, and sieving; C was determined by Leco combustion. The >2-mm fraction contained up to 46% of the whole-soil C and averaged 23% for the seven forests that had C in that fraction. Following treatment with sodium hexametaphosphate to disaggregate soil material, up to 20% of whole-soil C remained in the >2-mm fraction. Thus, the >2-mm fraction C appears to be in stable and unstable aggregates, as well as concretions. The whole-soil C in the surface 100 cm of mineral soil ranged from 30 to 400 Mg C ha^{-1}. Multiple regression analysis indicated this C pool was positively related to available water capacity, annual precipitation, and coarse woody debris (r^2 = 0.63 to 0.66, n = 18 forests). Similar results were obtained with only the <2-mm soil C, which is the basis of previous regional evaluations. This suggests consideration of the >2-mm fraction does not alter our understanding of the importance of climate and soil texture as controls of soil C pools, but it does affect the quantification of soil C pools in many old-growth forests in the Pacific Northwest.

Soil is a major pool in regional budgets and the global cycles of C (Jobbágy and Jackson, 2000; Zinke and Stangenberger, 2000; Bernoux et al., 2002; Goodale et al., 2002). Soil C content varies considerably within landscapes and between regions. It is influenced by climate, soil texture, topography, vegetation, and land management (Homann et al., 1995; Jobbágy and Jackson, 2000; Parker et al., 2001). There is considerable uncertainty associated with estimates of soil C pools and their association with controlling variables, because of sampling and analytical difficulties, soil spatial variability, and methods of extrapolation to regions (Homann et al., 1995, 1998, 2001; Brejda et al., 2001).

Most studies of soil C pools have measured only fine fractions of the soil, such as <2, <3, or <4 mm (Grigal and Ohmann, 1992; Canary et al., 2000; Parker et al., 2001; Brejda et al., 2001; Homann et al., 2001). Recent investigations of forests indicate the coarse fractions can also contain substantial C, and consideration of only the fine fraction would substantially underestimate the whole-soil C pool. For example, the <2-mm fraction contains only 63% of whole-soil C in a coastal Oregon forest (Cromack et al., 1999), 53 to 80% in three Australian forest sites (Bauhus et al., 2002), and 37% in one western Washington forest but 97% in another (Harrison et al., 2003).

Some >2-mm C may be associated with charcoal or rocks (Bauhus et al., 2002; Harrison et al., 2003). Alternatively, it may be contained in aggregates that are not broken down during routine sample processing. It is not clear to what extent the coarse fractions are physically stable, or if they readily reduce to <2-mm material under standard soil preparation procedures (USDA-NRCS, 1996).

Quantitative empirical relations between soil C and environmental controls are critical in parameterizing and testing dynamic models, and in estimating deeper soil C pools in areas where only the surface soil C has been measured. In forests of the Pacific Northwest, USA, Homann et al. (1995) found soil C increased with annual temperature, annual precipitation, actual evapotranspiration, clay, and available water-holding capacity, and decreased with slope. In a global assessment, Jobbágy and Jackson (2000) found the vertical distribution of soil organic C to be related to climate and vegetation type, with forests having a higher proportion of soil C concentrated nearer the surface. In assessments like these, data are compiled from various sources (Homann et al., 1995; Jobbágy and Jackson, 2000), which may have used a variety soil preparation and analytical methods (Homann et al., 1995). It is not clear if the results from these assessments are representative of whole-soil C, or only some fraction of it.

Our objectives were (i) to determine the extent to which the >2-mm fraction contributes to whole mineral-soil C pools in old-growth forests of the Pacific Northwest, (ii) to determine the stability of the >2-mm fraction, and (iii) to determine how the >2-mm C affects our interpretation of the relation of soil C pools to environmental controls. We also provide forest floor C pools to complement the mineral soil information.

MATERIALS AND METHODS

Site Description

Soil samples were collected from one to eight pedons in each of 18 forests distributed over five physiographic provinces in western Washington and Oregon (Table 1). The pedons were associated with previously established plots, which differ in number among the forests. The specific stands sampled within the forests are associated with the Andrews Long Term

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Abbreviations: LOI, loss on ignition.

Table 1. Characteristics of Pacific Northwest old-growth forests.

Forest code	Location	Stands†	Latitude	Longitude	Elevation	Tree age	Annual temperature‡	Annual precipitation§	Dominant tree species¶
			°N	°W	m	yr	°C	cm	
			Washington Coast						
A	Quinalt RNA	HS02, HS03	47° 26′	123° 52′	122	230	8.9	290	ss, wh
B	South Fork Hoh River	HR01, HR02, HR03, HR04	47° 47′	123° 55′	247	280	8.2	370	ss, wh
C	Twin Creeks RNA	HS04	47° 50′	123° 59′	152	230	8.9	300	ss, wh
			Oregon Coast						
D	Cascade Head	CH01, CH03, CH12	45° 03′	123° 54′	288	150	8.5	270	ss, wh
E	Cascade Head	CH04, CH05, CH07, CH08	45° 04′	123° 56′	258	150	8.9	260	ss, wh
F	Cascade Head	CH10	45° 04′	123° 59′	396	150	7.9	240	ss, wh
			Washington Cascades						
G	Carbon River	AV14, TO11	46° 59′	121° 52′	845	875	6.0	230	df, psf, wh
H	Nisqually River	AE10, AG05, AV06, TO04	46° 46′	121° 48′	1020	625	6.3	250	ac, df, psf, wh, wr
I	Ohanapecosh River	AO03, AV02	46° 50′	121° 33′	847	1000	6.0	230	psf, wh
J	White River	AB08	46° 55′	121° 32′	1050	500	7.3	210	wh, wr
K	Munger RNA	MUNA	45° 50′	121° 58′	411	470	7.8	250	df, wh
			Oregon Cascades						
L	HJ Andrews	RS20	44° 13′	122° 15′	700	450	10.4	190	df, sp
M	HJ Andrews	RS23, RS29	44° 14′	122° 08′	910	450	7.6	180	df, wh, wr
N	HJ Andrews	RS22, RS27, RS31	44° 16′	122° 10′	993	450	6.8	220	df, nf, wh, wr
O	Middle Santiam Hi	EPA-Hi	44° 23′	122° 10′	1219	210	7.6	204	df, psf
P	Middle Santiam Lo	EPA-Lo	44° 23′	122° 23′	536	105	10.3	201	df
			Oregon Eastside						
Q	Metolius RNA	MRNA	44° 29′	121° 38′	933	300	8.1	40	pp
R	Pringle Falls RNA	PF27, PF28, PF29	43° 43′	121° 37′	1359	433	5.6	50	lp, pp

† Official stand designation of Forest Sciences Data Bank, Oregon State University, Corvallis, OR, except for EPA-Hi and EPA-Lo.
‡ Temperature data was from the potential temperature (POTT) model (Dodson and Marks, 1997) for 1960–1990.
§ Precipitation data was from Precipitation-elevation Regressions on Independent Slopes Model (PRISM; Daly et al., 1994) for 1960–1990.
¶ Species abbreviations: ac, Alaska cedar, *Chamaecyparis nootkatensis* (D. Don) Spach; df, Douglas fir, *Pseudotsuga menziesii* Franco (Mirb.); lp, lodgepole pine, *Pinus contorta* Dougl.; nf, noble fir, *Abies procera* Rehd.; pp, Ponderosa pine, *Pinus ponderosa* Laws.; psf, Pacific silver fir, *Abies amabilis* (Dougl.) Forb.; sp, sugar pine, *Pinus lamberiana* Dougl; ss, Sitka spruce, *Picea sitchensis* (Bong.) Carr.; wh, western hemlock, *Tsuga heterophylla* (Rafn.) Sarg.; wr, western redcedar, *Thuja plicata* Donn.

Ecological Research (LTER) program and its network of permanent plots designed to observe and monitor changes in composition, structure, and functions of forest ecosystems over long time periods. A description of the history and characteristics of the network is provided in Acker et al. (1998). Mature to old-growth coniferous trees dominate each forest (Smithwick et al., 2002). Mean annual temperature ranges from 5.6 to 10.4°C, and mean annual precipitation from 40 to 370 cm (Table 1).

Forest Floor Pools

Forest floor samples were taken at five points above the sampling face of a pedon with a vertically oriented 5-cm diameter corer. The samples were composited for each pedon. The samples included woody debris <1 cm in diameter on the surface and all material within the forest floor that was not visible from the surface, including all woody debris irrespective of size.

Forest floor samples were oven dried (70°C), weighed, coarsely ground in a blender (Braun AG, Frankfurt, West Germany), and finely ground (<850 μm, <20 mesh) in a mill (IKA-A 10, Staufen, Germany). Samples were randomized before analysis of total C and N with a LECO CNS 2000 analyzer (Leco Corp., St. Joseph, MI).

The forest floor C pool (kg C m^{-2} dry mass) was determined as

$$\text{forest floor C pool} = C \times M/A \times 10 \qquad [1]$$

where C is the C concentration (g C kg^{-1} oven-dried mass), M is oven-dried sample mass (g), A is total cross-sectional area of the five subsamples (cm^2), and 10 is a units-conversion factor.

Mineral Soil Pools

Three mineral soil layers were sampled (0–20, 20–50, and 50–100 cm). Depth strata, as opposed to horizon, sampling was chosen because it is more repeatable and comparable with other studies that have assessed C pools. Mineral soil samples were obtained by collecting material in three swaths, 5- to 10-mm deep, across the pedon face within each layer. For the few pedon faces that were too rocky to make swaths, samples were collected as part of bulk density sampling.

The samples were air-dried and then processed with 2- and 4-mm sieves. Sieves were repeatedly shaken by hand and material was broken up with a rubber stopper repeatedly run over the surfaces of the sieves. Based on observed morphology and color, the resulting 2- to 4- and >4-mm fractions were sorted by hand into 2- to 4-mm C-bearing soil fraction, >4-mm C-bearing soil fraction, >2-mm rock (assumed non-C bearing), and >2-mm buried wood, roots, charcoal. The 2- to 4-mm C-bearing and >4-mm C-bearing soil fractions appeared to be spherical concretions or aggregates of the <2-mm material. Each component was weighed. The >2-mm buried wood, roots, and charcoal accounted for <3% of the sample masses, and were not considered as part of the soil C pools. Carbon bearing fractions >2 mm were analyzed for C only if they were >10%, by weight, of the whole sample. Otherwise, the weight of the >2-mm C-bearing fraction was incorporated into the rock mass used to estimate soil volume (see below).

Subsamples (50–100 g) of <2-, 2- to 4-, and >4-mm C-bearing fractions were obtained with a sample splitter (CL-280 series, SoilTest, Loveland, CO). These subsamples were ground to 850 μm (<20 mesh) using a 20-cm disc pulverizer (BICO Inc., Burbank, CA), dried at 60°C, and analyzed for total C and N concentration using a LECO CNS 2000 analyzer. Concentra-

tions were converted to a 105°C basis based on moisture determination of subsamples.

Bulk density methods varied with soil properties. For nonrocky soils, a 5-cm diam. by 5-cm deep soil-core bulk-density sampler with sampling ring inserts (AMS Inc., American Falls, ID) or a 5-cm diam. tube was used. Three cores were taken at various depths within each layer and composited by layer, resulting in one bulk-density sample for each of the three layers per pedon. For rocky pit faces, a cube was cut (approximately 20 by 10 cm by layer depth), the material excavated, and dimensions of the hole measured to determine excavated volume. The excavated material was processed in the field with a 20-mm sieve; the <20- and >20-mm fractions were weighed and subsampled for moisture content and further sorting and analysis. The estimated excavated volume may deviate from actual excavated volume by as much as 15%, based on an independent evaluation of 71 small excavated pits (P.S. Homann and B.T. Bormann, 2004, unpublished data).

Each air-dried bulk density sample was sieved and hand-sorted into the same components as the samples for C and N analysis, dried to 105°C, and weighed. Bulk density (g cm^{-3}) of C-bearing material, D_c, was calculated as

$$D_c = M_c/V/(1 - M_{2\text{–}75}/D_{2\text{–}75}) \quad [2]$$

where M_c (g) is the oven-dried mass of all C-bearing material; V (cm^3) is the sample volume; $M_{2\text{–}75}$ (g) is the mass of 2- to 75-mm rocks in the sample; and $D_{2\text{–}75}$ (g cm^{-3}) is the particle density of 2- to 75-mm rocks, which was assumed to be 2.65 g cm^{-3} for all pedons except the pumice at Pringle Falls which was assumed to be 2.1 g cm^{-3} (Flint and Childs, 1984). Because of their small contribution, buried wood, roots, and charcoal were omitted from the calculation.

The fractional volume of all C-bearing material, V_c, was calculated by rearranging the volume-estimate equation of USDA-NRCS (1996) to yield

$$V_c = (1 - V_{>75})/(1 + D_c/D_{2\text{–}75} \times M_{2\text{–}75}/M_c) \quad [3]$$

where $V_{>75}$ is the fractional rock volume of >75-mm rocks. The $V_{>75}$ was estimated in the field by examination of the pit face and making a visual estimate; or in cases where large rocks were abundant, the material extracted from the pit was separated into <75- and >75-mm fractions, and the relative amount of each fraction was estimated visually for each layer. Other variables are as defined in Eq. [2].

The mineral soil C pool (kg C m^{-2}) for each of three soil layers (0–20, 20–50, 50–100 cm) and each of three size classes (<2, 2–4, >4mm) was determined as

$$\text{Pool}_i = C_i \times D_c \times V_c \times M_i/M_c \times T \times 10 \quad [4]$$

where C_i is the total C concentration (g C kg^{-1} dry mass) of size class i; i refers to the <2-, 2- to 4-, and >4-mm C-bearing size classes; M_i is the oven-dried mass (g $sample^{-1}$) of material in size class i; T is layer thickness (cm), and 10 is a units conversion factor. Other variables are as defined in Eq. [2] and [3]. Whole mineral-soil C pools were obtained by summing the C pools of the three size classes.

Stability of 2- to 4-mm Fraction

The air-dried C-bearing 2- to 4-mm fraction from five samples from each province was treated with sodium hexametaphosphate solution [35.7 g $(NaPO_3)_6$ and 7.94 g Na_2CO_3 L^{-1}; USDA-NRCS, 1996] by two different methods. In the first method, a subsample was added to sodium hexametaphosphate solution, swirled for 1 min every 15 min for 1 h, allowed to set for 10 h, and swirled for 1 min every 15 min for an additional 1 h. In the second method, a subsample was added to sodium hexametaphosphate solution and shaken constantly for 12 h on an orbital shaker. After either treatment, the material was placed on a 2-mm sieve, rinsed with running water for 15 s, and air-dried. Before and after treatment, the 2- to 4-mm material was weighed, and analyzed for moisture content (105°C) and for loss-on-ignition (LOI) by heating at 450°C for 12 h. The LOI values and pretreatment LOI/C ratios were used to convert all values to C masses.

Statistical Methods

Comparisons of soil C pools among forests were made with a single-factor ANOVA, in which the forest was the factor and the pedon was the observational unit. Before analysis, soil C values were log-transformed to reduce heterogeneity of variance among forests. The influence of treatment on the stability of the 2- to 4-mm fraction was determined with a randomized block ANOVA, in which the soil sample was the block and the treatment was the factor. The least significant difference (LSD) test ($P < 0.05$) was used to separate means.

The relation of mineral soil C pools to site factors was determined with step-wise regression analysis (Homann et al., 1995). To avoid pseudoreplication, the average values for each of the 18 forests were used. A separate analysis was performed for each of four dependent variables: <2-mm C pool in 0- to 20-cm mineral soil, whole-soil C pool in 0- to 20-cm mineral soil, <2-mm C pool in 0- to 100-cm mineral soil, and whole-soil C pool in 0- to 100-cm mineral soil. These dependent variables were log-transformed to reduce heterogeneity of variance. The potential independent variables were potential evapotranspiration; actual evapotranspiration; mean annual precipitation; mean annual temperature; masses of sand, silt, and clay to 20- and 100-cm depths; available water holding capacities to 20- and 100-cm depths; and slope (Homann et al., 1995); as well as stand age, and masses of fine and coarse woody debris (Smithwick et al., 2002). To avoid multicolinearity, highly correlated ($r > 0.7$) independent variables were not included in the same regression model. Variables in final models were accepted at $P < 0.05$.

RESULTS AND DISCUSSION

Whole-Soil C

Forests with relatively small forest floor C pools (approximately 10 Mg C ha^{-1}) occurred in all five provinces, while forests with high amounts were found only in Oregon Coast, Washington Cascades, and Oregon Cascades (Fig. 1). The magnitude and variability of forest floor C pools is consistent with the assessment of western Oregon forests, including second-growth stands, in which forest floor C pools ranged from 1 to 110 Mg C ha^{-1} and averaged 20 Mg C ha^{-1} (Homann et al., 1995).

The C pool sizes of mineral-soil (Fig. 2) were more consistent within provinces than those of the forest floor (Fig. 1). Whole mineral-soil C pools in the upper 100 cm of soil ranged from 30 to 400 Mg C ha^{-1} (Fig. 2). The values were within the range of 23 to 880 Mg C ha^{-1} for western Oregon pedons (Homann et al., 1995), even though many of those assessments were for C in <2-mm fraction rather than both <2- and >2-mm fractions, as measured in this study.

The Oregon coast had the largest mineral-soil C pools and Oregon eastside had the lowest amounts (Fig. 2). This pattern is consistent with the spatial distribution

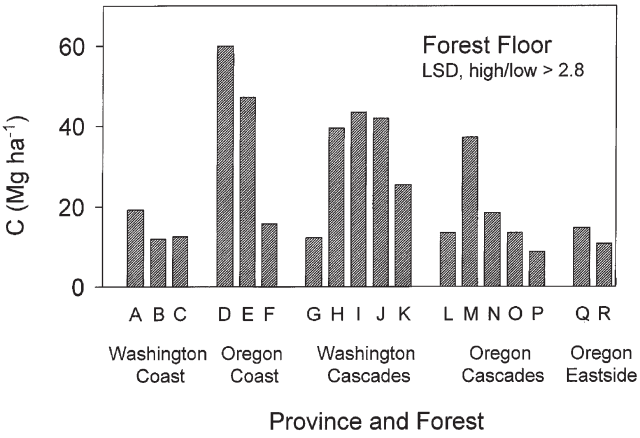

Fig. 1. Forest floor C pools of old-growth forests of the Pacific Northwest. Each bar represents a forest and is the average of 1 to 8 pedons (see Table 2). Pooled within-forest coefficient of variation (CV) is 77%. With $n = 4$ pedons per forest, a ratio of a higher mean to a lower mean >2.8 indicates two forests are significantly different, based on ANOVA of log-transformed values followed by the LSD test ($\alpha = 0.05$); exact cutoff value of ratios differs among pairs of forests because of different numbers of pedons at different forests.

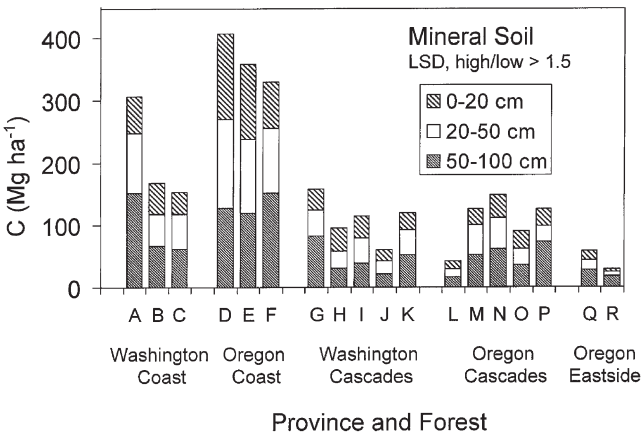

Fig. 2. Whole mineral-soil C pools of old-growth forests of the Pacific Northwest. Each bar represents a forest and is the average of 1 to 8 pedons (see Table 2). Pooled within-forest CV is 34%. With $n = 4$ pedons per forest, a ratio of a higher mean to a lower mean >1.5 indicates two forests are significantly different, based on ANOVA of log-transformed values followed by the LSD test ($\alpha = 0.05$); exact cut-off values of ratios differ among pairs of forests because of different numbers of pedons at different forests.

of soil C based on the state soil geographic database (Homann et al., 1998). Variation in C concentration, bulk density, and rock volume all contributed to the differences in C pools among forests (Table 2). For example, Washington coast forest A had higher C concentrations that more than offset low bulk density and high rock volume, to yield a higher mineral-soil C pool than other Washington coast forests. In contrast, low bulk density and high rock volume of Oregon Cascades forest L resulted in a low mineral-soil C pool in spite of C concentrations comparable to other Oregon Cascade forests (Table 2).

The nature of the C in soil samples likely depends on both natural processes and analytical procedures. We assume that most of the C in our study is organic. The high precipitation in most forests (Table 1) and the volcanic and glacial parent material (Heilman et al., 1981) make it unlikely the C is from carbonate, although we did not specifically test for this. Furthermore, small

Table 2. Average whole mineral-soil characteristics of Pacific Northwest old-growth forests.

		C concentration of non-rock material			N concentration of non-rock material			Bulk density of non-rock material			Rock volume		
		Depth, cm											
Forest code	n pedons	0–20	20–50	50–100	0–20	20–50	50–100	0–20	20–50	50–100	0–20	20–50	50–100
		g kg^{-1}						g cm^{-3}			% of total volume		
Washington Coast													
A	4	136	55	27	6.31	2.82	1.69	0.61	0.67	0.66	10	13	34
B	8	43	24	10	2.69	1.68	0.96	0.85	0.90	1.12	2	5	7
C	2	34	19	6	2.10	1.08	0.60	0.90	1.00	1.25	1	0	0
Oregon Coast													
D	7	116	74	34	5.40	3.70	1.77	0.62	0.69	0.87	7	5	2
E	8	122	74	35	6.08	3.80	2.08	0.51	0.55	0.72	0	1	2
F	2	172	80	35	9.32	4.17	1.84	0.45	0.49	0.59	2	11	32
Washington Cascades													
G	4	62	26	27	2.52	0.93	1.15	0.75	0.84	0.88	1	15	41
H	7	19	11	11	0.60	0.42	0.48	0.92	1.04	0.86	6	15	27
I	2	26	21	18	0.96	0.76	0.66	0.81	0.85	0.66	5	24	42
J	2	12	8	5	0.28	0.25	0.29	0.96	1.04	1.02	8	14	34
K	8	27	15	6	0.84	0.68	0.38	0.95	0.93	0.94	1	0	7
Oregon Cascades													
L	1	47	31	26	1.02	0.85	0.95	0.29	0.29	0.29	39	51	70
M	4	55	37	22	1.97	1.35	1.09	0.56	0.62	0.51	19	31	44
N	6	61	32	15	2.49	1.43	0.82	0.61	0.75	0.84	13	15	19
O	2	23	12	13	0.82	0.64	0.78	0.80	0.79	0.61	3	7	29
P	2	34	9	5	1.89	0.76	0.58	1.05	0.98	1.04	0	0	0
Oregon Eastside													
Q	4	15	5	3	0.55	0.28	0.25	1.00	1.15	1.23	6	8	15
R	6	14	3	2	0.47	0.19	0.16	0.64	0.62	0.82	3	3	8
Pooled within-forest CV, %		31	43	55	32	36	44	16	17	21	99	116	118

pieces (<2 mm) of charcoal may have contributed C in our samples, although large identifiable pieces of charcoal had been removed. Finally, we did not make C measurements of the material we classified as >2-mm rocks, although organic C may be present in sedimentary rocks (Des Marais et al., 1992), and rock has been mentioned as a possible pool of organic C in forest soils (Bauhus et al., 2002; Harrison et al., 2003).

Carbon in >2-mm Fractions

Seven of the 18 forests had C in the >2-mm mineral-soil fractions (Fig. 3). In the 0- to 20-cm layer, the >2-mm fractions contained as much as 46% of the whole-soil C, as observed in Oregon Cascade forest P. In general, the >2-mm fractions tended to contain lower proportions of whole-soil C at greater depths (Fig. 3). The occurrence and magnitude of >2-mm C-containing fractions in more than a third of the forests evaluated in this study supports the conclusion of Cromack et al. (1999) that these fractions can contribute substantially to soil C pools. They found 37% of soil C to be in >2-mm fractions. Harrison et al. (2003) found 63% of whole-soil C in >2-mm fractions at one western Washington site, but only 3% at another site. Bauhus et al. (2002) determined 20 to 47% of whole-soil C was in >2-mm fractions in three Australian forests.

In our study, much of the C in the >2-mm fractions appears to have been in aggregates or concretions that had composition similar to <2-mm material. This conclusion is supported by the sorting procedures and chemical characteristics of the fractions. The concentrations of C in the 2- to 4- and >4-mm C-bearing material were highly positively correlated with those in the <2-mm fractions ($r > 0.95$); similarly the concentrations of N in the 2- to 4- and >4-mm C-bearing material were highly positively correlated with those in the <2-mm fractions ($r > 0.95$). The C and N concentrations in the 2- to 4-mm C-bearing material averaged 15 to 16% less than in the <2-mm fraction ($P < 0.0001$, paired t tests), while there were no differences in concentrations between the <2 and >4-mm C-bearing material ($P > 0.4$, paired t tests).

The USDA-NRCS (1996) has developed detailed standard procedures to separate coarse fragment (>2-mm) fractions from the <2-mm fraction. The procedures differ among soil types. Soils without coarse fragments (>2 mm) are crushed in a laboratory jaw crusher. Clayey soils with many coarse fragments are sieved (2 mm) in a mechanical shaker. Soils with easily crushable coarse fragments are crushed with a rubber roller, and other soils are crushed with a wooden rolling pin, to pass a 2-mm sieve; the soils are rolled and sieved until only the coarse fragments that do not slake in a sodium metaphosphate solution remain on the sieve. The <2-mm fraction is saved for chemical analyses, while the >2-mm fractions are discarded following measurement of their masses. Hence, the implicit premise is that the >2-mm fractions are not chemically important for purposes undertaken by USDA-NRCS, such as soil classification and fertility assessments.

Our assessment indicated that the >2-mm fraction could contain a substantial amount of C, even following exposure to sodium hexametaphosphate to disaggregate soil materials (Fig. 4). Hence, the applicability of procedures designed for one purpose, for example, standard procedures to separate fine and coarse fractions, may bias results of other uses, for example, the estimation of total soil C. The importance of C in the >2-mm fraction varied among provinces. For Washington coast samples, the contribution of the 2- to 4-mm fraction to soil C became progressively lower with harsher treatment, while there was no effect of this treatment on the Washington Cascade samples (Fig. 4). Approximately 5 to 20% of the <4-mm soil C remained in the 2- to 4-mm fraction even with the severe treatment of shaking in sodium hexametaphosphate. These results indicate all size fractions need to be assessed for C (Harrison et al., 2003), irrespective of whether or not disaggregation procedures are used to separate the size fractions. Alternatively, the whole soil can be measured without fractionation or sieving (Binkley et al., 1992; Gerzabek et al., 2001).

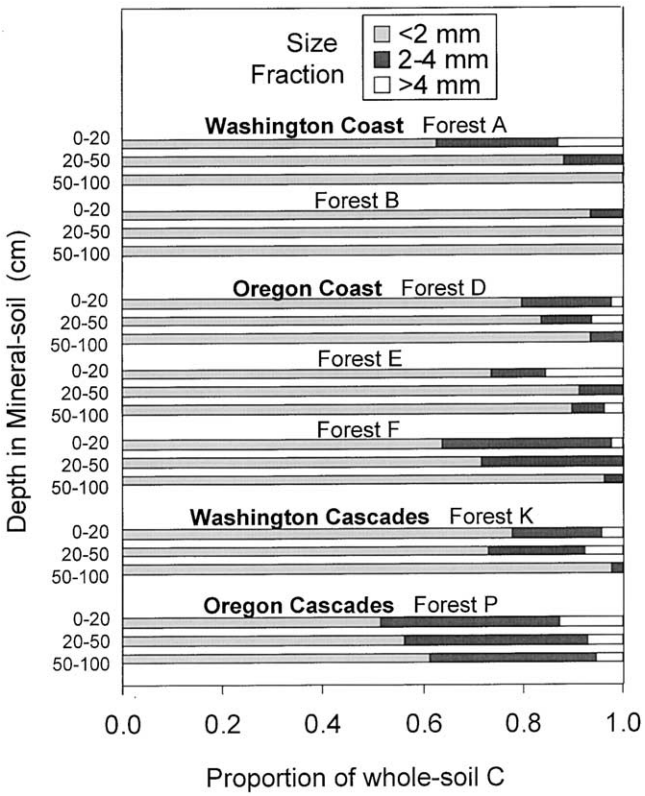

Fig. 3. Proportion of whole mineral-soil C in size fractions of Pacific Northwest old-growth forests. Only forest provinces with C in >2-mm fractions are shown. Each bar represents 1 to 8 pedons within a forest (see Table 2). Pooled within-cell (forest–depth combination) CV of <2-mm proportion is 15%.

Other studies that have identified C in >2-mm fractions have used a variety of soil preparation methods. Cromack et al. (1999) separated <2-mm from >2-mm fractions by air-drying (40°C) and sieving for 2 min on a motor-driven shaker sieve. Bauhus et al. (2002) obtained >2-mm fractions of air-dried soil that "did not disintegrate easily from the hand-applied pressure

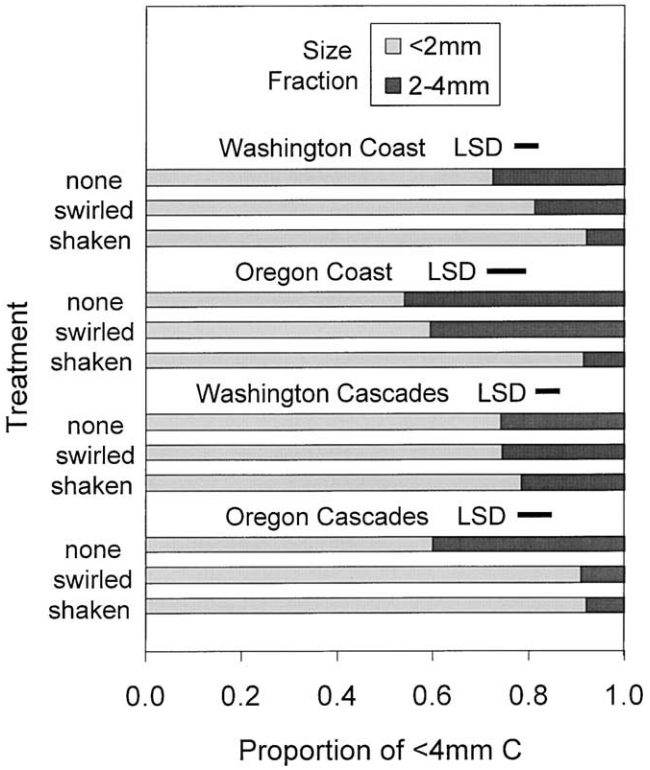

Fig. 4. Proportion of <4-mm C in size fractions of Pacific Northwest old-growth forest soils, as affected two different treatments: periodic swirling with sodium hexametaphosphate for 12 h, or constant shaking with sodium hexametaphosphate for 12 h. Each value is based on five soil samples that have C in both the <2 and 2- to 4-mm fractions. The LSD bars are based on randomized block ANOVA (soil is block) for each province, followed by LSD test ($\alpha = 0.05$).

during sieving." Harrison et al. (2003) air-dried samples to constant weight and then screened to 2 mm. Many studies of forest soil C, however, do not detail soil preparation and sieving procedures, other than to indicate analyses were made on <2-, <3-, or <4-mm fractions (Grigal and Ohmann, 1992; Canary et al., 2000; Parker et al., 2001; Homann et al., 2001). Hence, it is not clear how much effort was made to physically breakdown aggregates into smaller units that would pass through sieves and, hence, be counted in estimates of soil C. Further, it is not clear to how much soil C was missed by not measuring the coarser fractions.

The elucidation of the contribution of various soil physical fractions to C and nutrient dynamics is an ongoing challenge (Christensen, 1992). Advances in understanding might occur with long-term laboratory incubations of separated and recombined fractions, such as those performed with light and heavy density fractions of Pacific Northwest second-growth forest soils (Swanston et al., 2002, 2004).

Regional Controls on Soil Carbon

Regional evaluations can provide estimates of horizontal and vertical spatial patterns of soil C (Homann et al., 1998; Jobbágy and Jackson, 2000). The spatial patterns provide a basis to estimate extant soil C pools over large areas, which in turn, serve as a foundation for potential increases or decreases in response to pedogenesis, land use, and climate change (Sollins et al., 1983; Burke et al., 1989; Jenkinson et al., 1991; Bouwman and Leemans, 1995; Liski and Westman, 1997a). Regional evaluations also establish relations between soil C and possible controlling factors, such as climate and soil texture (Homann et al., 1995), which can be used in formulating and testing simulation models (Schimel et al., 1996; Thompson et al., 1996; Den Elzen et al., 1997; Post et al., 1997).

Consideration of soil C in >2-mm fractions did not influence our qualitative understanding of regional soil C distribution or its controls, but quantitative relations were influenced slightly. The vertical distribution of soil C was similar for the <2-mm fraction and the whole soil (Table 3). For the <2-mm fraction, the percentage of the 0- to 100-cm C in the 0- to 20-cm layer averaged 41%. For the whole soil, which included the >2-mm fractions, this percentage was only slightly higher at 42%. These values are in agreement with an average of 42% for western Oregon forests (Homann et al., 1995). However, the percentages are substantially lower than the average of 50% for forests around the globe (Jobbágy and Jackson, 2000). Relations of vertical soil C distribution to climate exacerbate the discrepancy. In an analysis of global forest soils (Jobbágy and Jackson, 2000), the average percentage in the 0- to 20-cm layer increased from 45 to 55% as average annual temperature decreased from 25 to 5°C. Furthermore, in low temperature (0–10°C) forests, the average percentage contributed by the 0- to 20-cm layer increased from 52 to 58% as annual precipitation increased to >1000 mm. Based on these trends, and the low annual temperatures and high precipitation of Pacific Northwest forests (Table 1), an average value >50% would be expected, in contrast to our observed average of 42%. The causes of this discrepancy between Pacific Northwest forests and relationships developed from global forests are unclear, but they could include seasonality of climate patterns, topographic influences, and soil textural effects.

The inclusion of >2-mm mineral-soil C did not qualitatively influence the relation of soil C to climate and site variables. The best stepwise regression equations for the whole-soil C and the <2-mm C were quite similar (Table 4), although the regression coefficients differed slightly. Available water capacity was a significant independent variable in accounting for the variation in soil C in both the 0- to 20- and 0- to 100-cm layers (Table 4). In combination with mean annual temperature, coarse woody debris mass, or precipitation, up to 84% of the soil C variation was explained.

These results are consistent with processes of soil organic matter production, stabilization, and decomposition (Sollins et al., 1996). The positive relation of soil C to available water capacity has also been observed in Lake States forests (Grigal and Ohmann, 1992), while the positive relation to precipitation has been found in a variety of forests and grasslands (Nichols, 1984; Sims and Neilsen, 1986; Burke et al., 1989; Grigal and Ohmann, 1992; Conant et al., 1998). Both precipitation and

Table 3. Proportion of the 0- to 100-cm mineral-soil C [mean (s.d.)] in soil layers of Pacific Northwest USA old-growth forests compared with global forests.

Layer depth, cm	Pacific Northwest–proportion of <2-mm C	Pacific Northwest–proportion of whole soil C	Globe–proportion of soil C†	P‡
0–20	0.41 (0.08)	0.42 (0.08)	0.50 (0.13)	0.02
20–50	0.31 (0.05)	0.31 (0.05)	0.29 (0.07)	0.2
50–100	0.28 (0.06)	0.27 (0.06)	0.21 (0.07)	0.001
n of forests	18		222	

† Global data synthesized from Jobbágy and Jackson (2000).
‡ P values are for two-sample t test that compares Pacific Northwest–proportion of whole soil C and globe–proportion of soil C. P values are approximate because standard deviations for globe were estimated from graphs in Jobbágy and Jackson (2000).

available water capacity are important for supplying water for primary production; in Pacific Northwest forests water storage is important because of potential water limitation during the dry summers (Waring and Franklin, 1979). Some of this production eventually becomes above- and belowground detritus, which contributes to soil C following decomposition. Available water capacity also reflects soil texture, which is important because of clay and silt stabilization of soil C (Sollins et al., 1996).

The negative relation of soil C to temperature is opposite that found in western Oregon forests (Homann et al., 1995). One possible explanation is that the relation found in this study is a statistical error, given the high *P* values of 0.04 for <2-mm C and 0.06 for whole-soil C. Alternatively, the interaction of temperature with other independent variables may cause different results; available water capacity was coupled with temperature in this study (Table 4), while precipitation and clay were the other independent variables coupled with temperature for western Oregon (Homann et al., 1995).

The positive relation of soil C to coarse woody debris may occur from direct causation or through indirect processes. The role of coarse woody debris in providing organic matter to the mineral soil is poorly understood. Coarse woody debris might provide direct inputs of organic matter to the mineral soil via leaching or embedding of wood into soil at the time of tree or snag fall. Alternatively, mechanisms of organic matter production and removal, such as by fire, might influence coarse woody debris and soil organic matter simultaneously.

CONCLUSIONS

Substantial soil C was present in the >2-mm fractions of one third of the Pacific Northwest old-growth forests we examined. The >2-mm fractions contained up to 46% of whole-soil C. The separation of C between <2- and >2-mm fractions is likely influenced by soil-preparation procedures; however, up to 20% of whole-soil C remained in the >2-mm fraction even after treatment with sodium hexametaphosphate, a standard NRCS procedure to disaggregate soil materials. Therefore, determination of soil C pools should include the >2-mm fraction, at least in initial assessments to determine the magnitude of that fraction at individual sites. In spite of the importance of C in the >2-mm fraction in some soils, consideration of this C does not substantially affect our understanding of the vertical distribution or the controls on soil C on a regional basis. Climate and soil texture variables continue to be important in explaining the spatial variation in soil C. Additionally, coarse woody debris may influence soil C in these old-growth forests.

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Table 4. Stepwise-regression relations of mineral soil C pools to site variables in Pacific Northwest old-growth forests (n = 18 forests).†

		Dependent variable			
		<2-mm C		Whole-soil C	
Layer depth, cm	Independent variables‡	Coefficient	P	Coefficient	P
0–20	constant	1.35	0.0001	1.16	0.0002
	available water capacity for layer, cm	0.22	0.0001	0.28	0.0001
	mean annual temperature, °C	−0.074	0.04	−0.070	0.06
	adjusted r^2	0.68		0.77	
0–20	constant	0.79	0.0001	0.66	0.0002
	available water capacity for layer, cm	0.17	0.0001	0.23	0.0001
	coarse woody debris, Mg ha^{-1}	0.0033	0.0002	0.0023	0.02
	adjusted r^2	0.84		0.79	
0–100	constant	1.2	0.0001	1.12	0.0001
	available water capacity for layer, cm	0.028	0.02	0.035	0.005
	mean annual precipitation, cm	0.0018	0.01	0.0017	0.02
	adjusted r^2	0.62		0.63	
0–100	constant	1.13	0.0001	1.11	0.0001
	available water capacity for layer, cm	0.038	0.0001	0.046	0.0002
	coarse woody debris, Mg ha^{-1}	0.0042	0.0006	0.0034	0.01
	adjusted r^2	0.74		0.66	

† Regression equations are of the form log (C, Mg ha^{-1}) = constant + coefficient1 × independent variable1 + coefficient2 × independent variable2.
‡ Ranges of independent variables: available water holding capacity, 2 to 6 cm for 0- to 20-cm layer and 11 to 25 cm for 0- to 100-cm layer; mean annual temperature, 5.6 to 10.4°C; coarse wood debris 4 to 139 Mg ha^{-1}; mean annual precipitation, 40 to 370 cm.

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